

GRAND CHALLENGES FOR STRUCTURAL DYNAMICS

Charles R. Farrar¹, David Brown², Izhak Bucher³, Mehmet Imergum⁴, Thomas L. Paez⁵

¹Engineering Analysis Group, MS P946, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

²Dept. of Mechanical Eng., 685 Rhodes Hall, Univ. of Cincinnati, P.O. Box 210072, Cincinnati, OH, 45221-0072

³Faculty of Mechanical Engineering, Israel Institute of Technology, Haifa, 32000, Israel

⁴Imperial College, Dept. of Mechanical Eng., Exhibition Rd, London, SW72BX, UK

⁵Experimental Mechanics, Dept. 9741 Sandia National Laboratory, Albuquerque, NM, 98124-2207

ABSTRACT

During the Structural Dynamics 2000 Forum held at Los Alamos National Laboratory in April, 1999, attendees were invited to submit ideas regarding Grand Challenge problems for structural dynamics. This paper will summarize the five ideas that were suggested. It is hoped that this paper will motivate others to suggest additional ideas and that open discussions of Grand Challenge Problems will become an integral part of future IMAC Conferences.

1. INTRODUCTION

For many years physicist and researcher in large-scale computational modeling have proposed grand challenges for their technological field. As an example, a current grand challenge being proposed by engineers and scientist involved in large-scale computational modeling is the development the technology to do global climate modeling. In the field of physics the development of grand challenge problems has proven to be a very effective method for publicizing technology beyond their technical community and generating large-scale research expenditures. Probably the most well known engineering Grand Challenge was the proposal in the early 1960's to place a man on the moon and return him safely to earth by the end of the decade. This extremely broad and ambitious Grand Challenge encompassed structural dynamics as well as many other engineering disciplines.

Attendees at the Structural Dynamics 2000 Forum held at Los Alamos National Laboratory in April, 1999 were invited to submit ideas for grand challenges related to structural dynamics. Some features of a grand challenge problem were established during the solicitation process. These features include:

1. The problem must be difficult and something that will not be readily solved in the next few years,

2. The problem must be multi-disciplinary in nature,
3. The problem must require development in experimental, analytical and computational methods,
4. There must be quantifiable measures indicating progress toward the problem solution,
5. The problem must be of interest to many industries, and
6. Solving the problem will have significant economical and social impact

This paper summarizes the five suggested grand challenges that were submitted at this Forum. No attempt is made to discuss the relative merits of these proposed grand challenges. To this end, the Grand Challenges are listed in alphabetical order of the proposing author's last name. It is hoped that this paper will stimulate a dialog within the structural dynamics community regarding appropriate grand challenges and motivate others to suggest additional ideas. Also, it is hoped that researchers will use these Grand Challenges to motivate funding agencies to pursue research in these areas. Finally, it is hoped that open discussions of Grand Challenge Problems will become an integral part of future IMAC Conferences.

2. PLANET EARTH SEISMIC ARRAY

Proposed by Dave Brown, University of Cincinnati

Measure, monitor, image and analyze the dynamics of planet earth, its seismic fault systems and its important infrastructures using a vast array of seismic and vibration sensors which are interconnected using the Internet.

2.1 Background:

This project involves measuring and modeling the dynamics of planet earth. Historically, there have been three major groups who have examined this problem. The first group is primarily basic scientists who are trying to understand the

physics and dynamics of the earth. They are probing the interior of the earth with seismic waves to better understand the physics of the core, the geology of the mantle, etc. This group utilizes an array of weak wave seismic monitoring stations for monitoring seismic waves. These stations are used for basic studies and for locating seismic events and nuclear tests. The second group is primarily concerned with monitoring earthquakes utilizing strong wave monitoring stations. The third group is involved with monitoring infrastructure. There are considerable overlaps between the three groups, but in general the measurement systems are independent.

One of the main objectives of this project is to develop a common measurement, data management and computational system for addressing the needs of these different disciplines. The measurement system will be distributed worldwide and consist of massive arrays of seismic sensors, primarily concentrated around important seismic sites.

The data is collected using the Internet and distributed to computational sites located on the Internet. This project will take advantage of the rapid changes that have taken place in the last decade in the areas of measurement, signal processing, computing and networking. Unlike most past scientific technological advancements, this project will be made possible by advancements in consumer products. The personal computer revolution, digital music, wireless communications, and the Internet are all key factors in making this Grand Challenge experiment possible.

2.2 What makes measuring, monitoring, imaging and analyzing the dynamics of planet earth a grand challenge?

- The integration of number of interconnected disciplines to help solve a basic science problem, which is to understand the dynamics of the planet.
- This project involves using a massive application of making distributed measurement and computations over the Internet. The recent advances in computers, networking, data acquisition, and consumer electronics make this possible.
- Installation of a vast array of seismic measurement nodes (100,000 or more) which can measure and image the geology of the planet.
- Utilization of low earth orbit satellite systems to synchronize and locate elements in the array (GPS) and to collect the vast amount of data and distribute it over the Internet (Teledesic Satellite System).
- Development of a series of inexpensive seismic measurement nodes (basic 4 channel node less than \$1000) which includes:
 - Multiple Sensors (accelerometers, strain gages, tilt sensors, etc)
 - Data Acquisition Module (24 bit dynamic range)
 - Re-circulating Digital Memory (128 Mbytes)
 - DSP Chip
 - GPS Timing and Position Module
 - Internet Communication Module (Wireless – Teledesic Satellite System)

- New inexpensive multi-element seismic sensors which can measure with nano G resolution (10^{-9} g's to 10g's)
- Distributed measurements for infrastructures using local area networks interfaced with master seismic node.
- Data distributed using the Ring Buffer Network Bus (RBNB) over the Internet
- Distributed computing using the Internet
- Development of new beam-forming and imaging algorithms for analyzing data from large seismic arrays. These algorithms need to be developed for parallel processing using a large number of computers distributed along the Internet. These algorithms need to be optimized for network communication.
- New computational algorithms for condition monitoring of infrastructures.

2.3 Goals demonstrating that the one can measure, monitor, image and analyze the dynamics of planet earth:

This Challenge is a major science project. The final goal of this project is the development of a measurement system utilizing a vast array of seismic sensors which can be used to measure the dynamics characteristics of the planet, its seismic faults systems, and its influences on infrastructure. This vast array tremendously improves the resolution and sensitivity of the current systems. It also will allow a much larger database to be collected during the large rare events where nonlinearities and other effects are present which cannot be interpolated from a linear model based upon small events.

- Since seismic waves are the only practical type of energy which can be used to probe the core of the earth, a system which can drastically expand the capabilities of existing systems to measure and image seismic waves is being developed. The primary goal of the basic science experiment is imaging the core of the earth and its mantle and developing models which can explain its motion, magnetic properties, etc.
- A practical and more immediate goal concerns the imaging and monitoring of seismic fault systems and predicting the influence of these faults systems on important infrastructures. Understanding seismic fault systems has significant social and financial impact on societies that are located in areas where there are active seismic faults systems.
- There will be significant scientific gain from this project:
 - Contributions to distributed measurement systems
 - Contributions to distributed computation systems.
 - Massive data management and distribution.
 - Measurement and signal processing which can be applied to many other types of health monitoring systems. Manufacturing, process control, and energy distribution systems are a few of the applications where there would be immediate impacts.
- The scope and size of this project rivals other scientific projects for exploring the universe.

3. Micro Electro Mechanical Systems

Proposed by Izhak Bucher, Israel Institute of Technology

Develop tools and methods for studying the dynamics of Micro Electro Mechanical Systems (MEMS)

3.1 Background:

The human kind often saw the greatest achievements of engineering in systems and structures having extreme size and proportions. During the 20th century huge buildings, bridges and machines were built, almost to an extent where size seems to have reached the largest reasonable proportions. New challenges arise in the other extreme namely, very small vibrating systems. Such systems although quite similar at a first glance to ordinary structures have special features attributed to their size as compared to atomic scale. Micro electro-mechanical systems (MEMS) are being used as sensors, microphones and actuating devices, all requiring a thorough understanding of their dynamical behavior. A small sensing device having a capacitive measuring device, for example, must be modeled as a coupled electro-dynamic system rather than treating the elastic and electrical parts separately. In micron scale, the electro-static forces, the damping due to viscosity of the surrounding fluid and other effects, which could be neglected when dealing with ordinary sized structures, become very important. These tiny devices are very attractive due to their inexpensive manufacturing process (developed for micro-electronics) and the potential to include sensors and actuators in places they were never considered before.

Due to lack of knowledge, practitioners use very simple and inadequate models that postpone the appearance of MEMS in many aspects of our lives. The challenge in this field is the formulation representative models and experimental verification of each mechanism, e.g. vibration, damping, fluid-structure interaction, influence of electrostatic forces.

3.2 What makes the development of tools and methods for studying the dynamics of MEMS a grand challenge?

- Micro mechanical systems (MEMS) have a great commercial potential
- The dynamic response of MEMS is one of the most important factors in their performance
- New effects that exist in small scale (electro-static), e.g. loading due to non-contacting sensing devices must be understood
- Small scale makes experimental verification very difficult
- The validity of elasticity which forms the basis for vibration theory must be validated

3.3 Goals demonstrating that adequate tools and methods have been developed for studying the dynamics of MEMS.

- Progress in this field will create a large range of products that will affect products from cars to medical instruments within 2-5 years

- In 2-4 years Every car would have a MEMS 5-10 rate gyros which costs \$4 and control the stability of motion, acceleration and be a navigation aid.

4. Perform robust global vibration-based damage assessment of engineering systems

Proposed by Charles Farrar, Los Alamos National Laboratory

4.1 Background:

The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the aerospace, civil and mechanical engineering communities. Current damage-detection methods are either visual or localized experimental methods that require the vicinity of the damage to be known *a priori* and that the portion of the structure being inspected is readily accessible. The need for quantitative global damage detection methods that can be applied to complex structures has led to research of methods that examine changes in the vibration characteristics of the structure. The basic premise of vibration-based damage detection is that the damage will significantly alter the stiffness, mass or energy dissipation properties of a system, which, in turn, will alter the measured dynamic response of that system. Although the basis for vibration-based damage detection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower-frequency global response of structures that is typically measured during vibration tests. This challenge is supplemented by many practical issues associated with making accurate and repeatable vibration measurements at a limited number of locations on structures often operating in adverse environments. Over the last thirty years global vibration-based damage detection has been applied to numerous aerospace, civil and mechanical structures as part of research studies. However, to date, only in the rotating machinery industry has this technology made the transition from a topic of research to actual implementation as a standard diagnostic tool.

4.2 What makes performing robust, global vibration-based damage assessment a grand challenge?

- All portions of our technical infrastructure require damage detection.
- Successful development of this technology will have tremendous economic impact by reducing unscheduled down time of manufacturing equipment, making damage assessment after earthquakes a quantifiable process and maintaining our transportation infrastructure in operating order.
- Early detection of damage in systems such as bridges and aircraft will have positive life safety implications.
- This problem has been worked on for many years and, most likely, will not be solved in the next 2-3 yrs.
- This problem requires a multi-disciplinary approach to its solution. (vibration analysis (linear and nonlinear);

vibration measurement; signal processing; sensor development; statistical analysis; and remote data acquisition, processing and transmission)

- Current measurement and data analysis technology does not allow for sufficiently precise quantification of damage-sensitive dynamic properties.

4.3 Goals demonstrating that one can perform robust global vibration-based damage assessment

- Within fifteen years the state of California mandates that every new building requiring strong motion instrumentation is also fitted with a vibration-based structural health monitoring system.
- Within ten years the micro-electronic manufacturing industry can reduce plant costs by eliminating 50% their redundant mechanical equipment.
- Within fifteen years annual scheduled maintenance costs of commercial aircraft are reduced 10% because inspection intervals have been increase as the result of in-service structural health monitoring.

5. ACCURATE PREDICTION AND MINIMISATION OF NOISE FOR ENGINEERING STRUCTURES

Proposed by Mehmet Imergum, Imperial College

5.1 Background:

The ability to minimize the noise produced by engineering structures at the earliest possible design stage is a major requirement throughout the aerospace, civil, mechanical and marine engineering communities. Current noise prediction methods are either based on experimental techniques that require trial-and-error adjustments to an existing prototype, or consist of semi-analytical techniques that can only deal with a limited number of simplified geometries. The subject area is truly multi-disciplinary as it is not always possible to distinguish between various origins of noise: structural vibration through a multitude of transmission paths, aero-acoustic effects, fluid-structure interaction, electro-magnetic effects, propagation of noise in air, water or other media, etc. Typical examples include train noise for passengers and the environment, aircraft engine noise for landing and take-off, submarine noise, noise generated by everyday tools that have rotating parts, etc.

The most difficult challenge is the formulation of accurate and representative models that can contain all required ingredients: structural vibration, unsteady aerodynamics, fluid-structure interaction, propagation of noise in compressible and incompressible flows. Currently, some of the required analytical/numerical tools are available but huge gaps exist between the various disciplines involved.

5.2 What makes accurate prediction and minimization of noise a Grand Challenge?

- All portions of our technical infrastructure require noise prediction.
- The rules regarding noise emission are becoming more and more stringent.

- For general geometries, there are no clear theoretical links between structural vibration and structure-borne sound.
- The structural (FE) models are not accurate for predicting higher modes of vibration and for dealing with damping.
- There are no established rules for ranking similar designs.
- It is not clear if statistical methods or large numerical models should be used.
- This problem has been worked on for many years and, most likely, will not be solved in the next 5-10 years
- The amount of detail that must be incorporated into the numerical models is not known.
- The noise source and the required location of the prediction can be separated by large distances.
- This problem requires a multi-disciplinary approach to its solution. (linear and non-linear vibration analysis, fluid-structure interaction, unsteady aerodynamics, sound propagation in air, water, etc.)

5.3 Goals demonstrating that accurate prediction and minimization of noise has been achieved:

The permissible noise levels for engineering products (aero-engines, car exhausts, lawnmowers, submarines, etc) are reviewed almost every year. A reduction of about 1 dB per year is becoming the expected norm.

6. COMPUTATION OF PROBABILISTIC STRUCTURAL DYNAMIC RESPONSE

Proposed by Tom Paez, Sandia National Laboratory

Perform accurate structural dynamic analysis of randomly excited, stochastic systems.

6.1 Background:

Numerical models of complex, structural dynamic systems have been constructed since the 1950's and used to analyze system response. Such analyses have been used to predict and assess system behavior, to design and optimize systems, and for many other purposes. Normally, numerical models of structural dynamics systems use nominal, deterministic values for parameters, and predict a single deterministic response. Yet, it is widely acknowledged that actual physical systems have parameters that vary randomly because system geometries are random, as are material properties, initial conditions, boundary conditions, and other system characteristics and conditions. Moreover, most of the inputs that excite dynamic system responses are random. These physical systems, their conditions, and their excitations may be termed stochastic, and their responses must be characterized in a probabilistic framework.

In view of these things, we require analytic approaches and software implementations of these approaches to accurately predict the responses of real systems. To assure that predictions produced by the software and the mathematical models constructed within the software

framework are satisfactorily accurate, predictions must be capable of being validated using formal, perhaps statistical, procedures. The software should at least have the following features:

- The computer code should be robust and user-friendly, usable by anyone with a basic understanding of structural dynamics and probability and statistics.
- It should handle relatively large, practical problems over a frequency range of interest to structural dynamicists (say 0 through 2000 Hz) where there is discrete or continuous randomness in the excitations, material properties, geometry, initial conditions, boundary conditions, component connections, etc.
- The analysis must permit random quantities to be Gaussian or non-Gaussian.
- It must permit the definition of temporal excitations as deterministic, random stationary, random non-stationary, or a combination of all three.
- It must permit the definition of random fields (spatial random processes) as homogeneous (steady state in a spatial sense) or non-homogeneous.
- It must permit the modeling of structural characteristics as linear or nonlinear.
- It must efficiently handle both shock and vibration problems.
- The computer code must have options for time and frequency domain analysis, and must permit the extraction of structural characteristics in any form.
- The mathematical models constructed within the software framework must be capable of being updated as new, experimentally measured excitation and response data become available.
- All this must be done accurately and efficiently, and the results must be capable of being validated using experimental results.

6.2 What makes performing accurate structural dynamic analysis of randomly excited, stochastic systems a Grand Challenge?

This is a Grand Challenge because:

- Even current deterministic computer codes that support the mathematical modeling of mechanical systems cannot accurately predict the detailed response of simple mechanical systems, much less the detailed response of complex systems over a practical range of frequencies.
- The probabilistic approaches required to create the software described above do not yet exist in their entirety.

6.3 Goals demonstrating that Perform accurate structural dynamic analysis of randomly excited, stochastic systems exists:

The challenge will be considered to have been met when:

- General techniques for solution of this problem are developed and proven via multiple comparisons to experiment.

- The solution techniques are made efficient enough for widespread application.
- Analysts, designers, and testers use code for the prediction of mechanical system response.

7. Summary

The concept of proposing "Grand Challenges" immediately generates some controversy as it reflects individuals, or groups of individuals, opinions regarding the relative difficulty, importance, and impact of various technical activities. As one might expect, lively discussions ensued after the Grand Challenges were presented at the Structural Dynamics 2000 Forum. Various technical aspects of each proposal were discussed along with issues regarding the possibility for achieving the stated goals for each activity.

The discussions that followed the presentations of the Grand Challenges addressed the issue that many of the proposed challenges have already been the focus of significant research efforts for many years. This statement is certainly true for all the challenges proposed at this Forum and for Grand Challenges proposed in other fields as well. The concept of a Grand Challenge for structural dynamics is not intended to develop some new application for this technology that has not been thought of previously. Rather, the intent is to focus attention of the technical community and funding agencies on important large-scale problems in an effort to achieve a more coordinated and cost-effective means of developing the proposed technology.

A general consensus arrived at in these discussions was that a certain amount of synergy exists between the various topics. As an example, the development of the planet earth seismic array will be closely coupled to developments of MEMS technology, the vibration-based damage assessment technology, and the probabilistic modeling technology. Similarly, accurate prediction and minimization of noise will benefit from developments in probabilistic modeling and MEMS.

Although the development of probabilistic modeling and MEMS were viewed as directly contributing to the other three Grand Challenges, it was suggested that these two technologies would develop somewhat independently from the other three Grand Challenges. The reason for this speculation is that the planet earth seismic array, global vibration-based damage detection and prediction and minimization of noise will make use of, and provide motivation for, the development of MEMS and probabilistic modeling technology. However, in general, these three challenges will not provide technologies that will address issues associated with the development of MEMS sensors or probabilistic modeling algorithms.

Discussions also focused on issues related to the impact of traditional and emerging structural dynamics technology on the various Grand Challenges. In general, it was recognized that the proposed topics are *challenging* because current and traditional technologies do not adequately solve these problems. As discussed previously, some of the proposed challenges themselves are related to the development of the technologies needed to address the other challenges.

Solving the proposed challenges will rely significantly on the development of a variety of emerging technologies spanning different engineering and mathematical disciplines. In turn, it is hoped that the Grand Challenge concept will then motivate further development of these various emerging technologies.

A characteristic of a Grand Challenge discussed in the introduction was that the solution to, or even progress toward the solution of, the Grand Challenge should have significant and positive economic and societal impact. To some degree, market economies provide a system that predisposes the solution of the Grand Challenge to have a positive economic and societal impact. Government agencies do not have a history of funding long-term, high-expenditure engineering projects that do not have positive economic or life-safety impact. Private industry is even less inclined to provide funding for projects that do not have such impact. It may be argued that some large scale government funded engineering projects that would fit the Grand Challenge concept, the most well known being manned-space mission to the moon, may not have started out with economic and societal issues as their primary objective. However, an after-the-fact review shows that the technology developed for such projects has had tremendous economic and societal impact. In the case of the manned mission to the moon, technology developed for this project has been used to provide satellite communications, which have a tremendous impact on global business. The space program has also had positive impact on people's day to

day life through the enhanced weather tracking capabilities provided by satellites. In the case of extreme weather, this tracking capability can have significant life safety implications as recently demonstrated during a hurricane on the east coast of the United States.

With regards to economic and societal impact, the proposed grand challenges must be viewed in terms of enabling technologies versus end-use technologies. Micro electromechanical sensors and probabilistic modeling technology do not in themselves provide significant and positive economic or societal impact. Rather these technologies provide tools for use in applications that can have such impact. The seismic array, noise reduction and damage detection challenges all have the potential to provide significant societal benefits, such as life safety and quality of life, as well as economic benefits.

It is realized that there are many other possible Grand Challenges for structural dynamics. The question that arises is how to develop a forum where various Grand Challenge ideas can be proposed, discussed, debated, archived and disseminated. A subsequent question that must be addressed is how to best use the concept of Grand Challenges to advance the state of the art in structural dynamics. Finally, in a related matter, how does the structural dynamics community get the buy-in from funding agencies and the private sector that the proposed Grand Challenges are of interest and worth pursuing?